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Grant N00014-90-J-1193

TECHNICAL REPORT No. 86

Coefficients of the Second Viscosity in Bulk Liquid Helium

by

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Prepared for publication

in

Physical Review B

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Pullman, WA 99164-1046



June 1992

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92-17456



REPORT DOCUMENTATION PAGE

Form Approved
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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 1992		3. REPORT TYPE AND DATES COVERED Interim	
4. TITLE AND SUBTITLE Coefficients of the Second Viscosity in Bulk Liquid Helium				5. FUNDING NUMBERS Grant N00014-90-J-1193	
6. AUTHOR(S) Chung-In Um, Chul-Won Jun and <u>Thomas F. George</u>					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Departments of Chemistry and Physics Washington State University				8. PERFORMING ORGANIZATION REPORT NUMBER WSU/92/86	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 800 N. Quincy Street Arlington, Virginia 22217				10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES Prepared for publication in <u>Physical Review B</u>					
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The coefficients of the second viscosity in bulk liquid helium are evaluated explicitly as a function of temperature via interactions between the anomalous excitation spectrums. The four coefficients of the second viscosity exhibit a T^{-1} dependence at low temperatures (well below 0.6 K), which is due to three-phonon processes originating from the anomalous dispersion at very low momenta and temperatures.					
14. SUBJECT TERMS SECOND VISCOSITY COEFFICIENTS BULK LIQUID HELIUM EXCITATION SPECTRA INVERSE TEMPERATURE DEPENDENCE THREE-PHONON PROCESSES				15. NUMBER OF PAGES 16 16. PRICE CODE NTIS	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT		

Coefficients of the second viscosity in bulk liquid helium

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The coefficients of the second viscosity in bulk liquid helium are evaluated explicitly as a function of temperature via interactions between the anomalous excitation spectrums. The four coefficients of the second viscosity exhibit a T^{-1} dependence at low temperatures (well below 0.6 K), which is due to three-phonon processes originating from the anomalous dispersion at very low momenta and temperatures.

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PACS Nos: 67.40.Hf, 67.40Pm

Since Peshkov¹ has confirmed experimentally the existence of a temperature wave called the second sound in bulk liquid helium, Landau² evaluated at first the ordinary second sound velocity in terms of the macroscopic thermal quantities and later derived the second sound as a collective density wave in the elementary excitation spectrum. Transport coefficients, i.e., thermal conductivity, viscosity and other kinetic coefficients, were also calculated above 0.6 K by means of kinetic equations by Landau³ and Khalatnikov.⁴

It is well known that at low temperatures and low pressures the thermal properties of superfluid helium are dominated by low-momentum phonons, which do not possess the normal dispersion, but rather an anomalous dispersion. In fact, these two cases are quite different in microscopic processes. The former is governed by four-phonon processes (4PP) while the latter is by three-phonon processes (3PP). Recently, several authors⁵ have evaluated the temperature variations of the first and second sound by using the wrong normal dispersion. However, in recent articles,⁶ we have derived a Landau-type elementary excitation spectrum, which has anomalous phonon-like behavior and roton-like behavior at low and high momenta, respectively, through the ring-diagram approximation in two- and three-dimensional liquid helium. In the bulk case, the obtained excitation spectrum is given by

$$E(p) = c_0 p [1 + \delta_1 p^2 - \delta_2 p^3 + \delta_3 p^4 + \dots] , \quad (1)$$

$$E(p) = \Delta + \frac{(p - p_0)^2}{2\mu} , \quad (2)$$

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where Δ , P_0 and μ are the roton parameters, c_0 is the sound velocity at absolute zero temperature, and δ_1 and δ_2 are positive constants which can be determined by the potential parameters. Here, we have adopted a soft potential with a Lennard-Jones-type tail, which helps make a smooth connection between the attractive part and a soft repulsive core. Using these excitation spectrums, we have successfully derived and explained the various sounds,⁷ sound attenuations⁸ and transport coefficients⁹ in two-dimensional and three-dimensional liquid ^4He .

Concerning the coefficients of the second viscosity in bulk liquid helium, recently Kirkpatrick and Dorfman¹⁰ evaluated these coefficients at very low temperature ($na\lambda^1 \gg 1$) on the basis of their kinetic equations¹¹ for a dilute superfluid, where n , a and λ represent the number density, s-wave scattering length and thermal wave length, respectively. In a previous paper¹² we have successfully evaluated the coefficients ζ_1 , ζ_2 , ζ_3 and ζ_4 of the second viscosity in two-dimensional liquid ^4He as a function of temperature by solving the superfluid hydrodynamics through the theory of the kinetic phenomena developed by Khalatnikov.

In this paper, adopting the above theory, we carry out a three-dimensional calculation to evaluate the coefficients of the second viscosity of bulk liquid helium via 3PP in the region of very low temperatures, which was not done by Landau and Khalatnikov. Near zero temperature, the important mechanism is 3PP: the direct process of emission of a phonon \vec{p} by $\vec{p}_1 \rightarrow \vec{p}_2 + \vec{p}$ and the reverse process of absorption of a phonon \vec{p} by $\vec{p}_2 + \vec{p} \rightarrow \vec{p}_1$. The differential decay rate for 3PP in three-dimensions is defined as

$$d\omega = \frac{2\pi}{\hbar} |\langle F | H_3 | I \rangle|^2 \delta(E_F - E_I) \frac{v^2 d\vec{p}_2 d\vec{p}}{(2\pi\hbar)^6}, \quad (3)$$

where H_3 is the Hamiltonian for 3PP.⁹ The transition amplitude between the temperature-dependent initial state $|I\rangle$ and final state $|F\rangle$ for the direct process is given by⁹

$$\begin{aligned} \langle F|H_3|I\rangle = & \frac{3!}{2} \frac{(2\pi\hbar)^3}{(2V)^{3/2}} \delta(\vec{p}_1 - \vec{p}_2 - \vec{p}) \left\{ \left(\frac{c_0 p}{\rho p_1 p_2} \right)^{\frac{1}{2}} (\vec{p}_1 \cdot \vec{p}_2) + \frac{\rho^2}{3c_0^2} \frac{\partial}{\partial \rho} \left(\frac{c_0^2}{\rho} \right) \right. \\ & \left. \times \left(\frac{c_0 p_1 p_2 p}{\rho} \right)^{\frac{1}{2}} \right\} [n_{p_1} (n_{p_2} + 1) (n_p + 1)]^{\frac{1}{2}}. \end{aligned} \quad (4)$$

Here n_p is the phonon distribution function with momentum \vec{p} . In the case of the reverse process, the last bracket in Eq. (4) should be replaced by $[(n_{p_1} + 1) n_{p_2} n_p]^{\frac{1}{2}}$. Then the total decay rate for the direct process becomes

$$\omega_D = \frac{\pi c_0}{2\hbar \rho} (u+1)^2 \int p_1 p_2 p n_{p_1} (n_{p_2} + 1) (n_p + 1) \delta(E_F - E_I) \frac{d\vec{p}_2}{(2\pi\hbar)^3}, \quad (5)$$

where $u = (\rho/c)(\partial c/\partial \rho)$ is the Grüneisen constant. For the reverse process, $n_{p_1} (n_{p_2} + 1) (n_p + 1)$ is replaced by $(n_{p_1} + 1) n_{p_2} n_p$.

From the total decay rate for the direct and reverse processes, the collision integral for the 3PP becomes

$$J_{3pp} = - \frac{\pi c_0}{2\hbar \rho} (u+1)^2 \int p_1 p_2 p \delta n (n_{p_{10}} - n_{p_{20}}) \delta(E_F - E_I) \frac{d\vec{p}_2}{(2\pi\hbar)^3}, \quad (6)$$

where δn is equal to $n_p - n_{p_0}$, and $n_{p_{10}}$ and $n_{p_{20}}$ represent the equilibrium

distribution functions for the phonons with momenta \vec{p}_1 and \vec{p}_2 , respectively. Since 3PP occur largely in the small angle events, the phonon distribution, which depends on the chemical potential α' ,¹³ can be written as

$$n = (\exp[(\alpha' + pc)/k_B T] - 1)^{-1}, \quad (7)$$

and expanding δn in a power series in terms of α' , we obtain $\delta n = n - n_0 = -n_0(n_0 + 1)\alpha'$. The relation⁴ between the collision integral and the kinetic coefficient can be expressed by

$$\frac{1}{k_B T} \int J_{3PP}(n) \frac{d\vec{p}}{(2\pi\hbar)^3} = \alpha' \Gamma_{3PP}, \quad (8)$$

and solving Eq. (8) for the kinetic coefficient, we get

$$\Gamma_{3PP} = \frac{3! \pi^2 (3)(u+1)^2}{60 \hbar^7 \rho c_o^8} (k_B T)^7. \quad (9)$$

To obtain the coefficients of the second viscosity, we follow the calculation in the third way given by Khalatnikov and show below only the results near absolute zero temperature:

$$\zeta_1(T) = \frac{9N^2_{ph}(T)}{\rho \Gamma_{3PP}} \left(\frac{\rho}{c} \frac{\partial c}{\partial \rho} \right)^2, \quad (10)$$

$$\zeta_2(T) = \frac{9N^2_{ph}(T)}{\Gamma_{3PP}} \left(\frac{\rho}{c} \frac{\partial c}{\partial \rho} \right)^2, \quad (11)$$

$$\zeta_3(T) = \frac{9N_{ph}^2(T)}{\rho^2 \Gamma_{3PP}} \left(\frac{\rho}{c} \frac{\partial c}{\partial \rho} \right)^2, \quad (12)$$

$$\zeta_4(T) = \zeta_1(T). \quad (13)$$

Here, the Grüneisen constant comes from differentiation of N_{ph} with respect to ρ and can be taken as constant near absolute zero temperature. $\zeta_1(T)$ and $\zeta_4(T)$ are equal and thus satisfy Onsager's reciprocity symmetric principle. $N_{ph}(T)$ is the number of phonons per unit volume at temperature T , and taking up to order p^4 in Eq. (1), we can express this as

$$N_{ph}(T) = \alpha_0 T^3 [1 + \alpha_1 T^2 + \alpha_2 T^3 + \alpha_3 T^4], \quad (14)$$

where

$$\begin{aligned} \alpha_0 &= \frac{36 \cdot 4! \zeta(4)}{\pi^3} \left(\frac{k_B}{hc_0} \right)^3, & \alpha_1 &= \frac{3 \cdot 6! \zeta(6)}{4! \zeta(4)} \delta_1 \left(\frac{k_B}{c_0} \right)^2, \\ \alpha_2 &= \frac{4 \cdot 8! \zeta(8)}{4! \zeta(4)} \delta_2 \left(\frac{k_B}{c_0} \right)^3, & \alpha_3 &= \frac{5 \cdot 8! \zeta(8)}{4! \zeta(4)} \delta_3 \left(\frac{k_B}{c_0} \right)^4. \end{aligned} \quad (15)$$

For numerical calculations, we have adopted the parameters which were deduced from the analysis of the elementary excitation of the bulk liquid helium data,^{6,14} as listed in Table 1. We have also taken the numerical value of u to be 1.8.¹⁵ Using these parameters and substituting Eqs. (9) and (14) into Eqs. (10)-(12), we obtain

$$\zeta_1(T) = \frac{6.313 \times 10^{-4}}{T} A(T) , \quad (16)$$

$$\zeta_2(T) = \frac{9.156 \times 10^{-5}}{T} A(T) , \quad (17)$$

$$\zeta_3(T) = \frac{4.355 \times 10^{-3}}{T} A(T) , \quad (18)$$

where

$$\begin{aligned} A(T) = & 1 + 2\alpha_1 T^2 - 2\alpha_2 T^3 + (2\alpha_3 + \alpha_1^2) T^4 \\ & - 2\alpha_1 \alpha_2 T^5 + (\alpha_2^2 + 2\alpha_1 \alpha_3) T^6 + \dots \end{aligned} \quad (19)$$

In Eqs. (16)-(18), all four coefficients include various T-dependent terms. The T^{-1} dependence also appears as the main contribution in the coefficient of the first viscosity,⁹

$$\eta(T) = \frac{3! \zeta(3) \zeta(2) \rho c_0^2}{\pi^5 k_B (u+1)^2} \frac{1}{T} = 1.90 \times 10^{-1} \frac{1}{T} . \quad (20)$$

This means that as the temperature approaches absolute zero, the roton contribution disappears, and thus the main contribution comes from 3PP. Therefore, the temperature dependence of the first viscosity coefficient is changed dramatically from T^{-5} to T^{-1} .

Kirkpatrick and Dorfman¹⁰ have introduced the classical kinetic theory technique to derive two-fluid hydrodynamics in an expansion of the unknown functions in terms of orthogonal polynomials, keeping only the first term, which represents the first Enskog approximation in the classical theory.¹⁶ They have also introduced an isotropic linear collision operator L that can be divided into two types of collision processes: an excited particle scatters with a condensed particle to produce two excited particles, or vice versa (L_{12}), and two excited particles scatter with each other and produce two new excited particles (L_{22}). These two processes correspond exactly to the processes 3PP ($\vec{p}_1, \vec{p}_2 \rightleftharpoons \vec{p}_3 + \vec{p}_4$) and 4PP ($\vec{p}_1 + \vec{p}_2 \rightleftharpoons \vec{p}_3 + \vec{p}_4$). The collision

operator L_{12} holds only for very small momenta. When the number of particles decreases with decreasing temperature, there are not enough collisions to keep a local equilibrium, and thus their hydrodynamic solution breaks down, which may also occur in very dilute classical gases. This means that Kirkpatrick and Dorfman have not taken into account 3PP, but only 4PP.

A finite lifetime of an elementary excitation in a quantum liquid originates from two processes: one is the collision between elementary excitations, and the other is the spontaneous decay of a phonon into two, three or more phonons. Since the collision probability tends to zero at very low temperatures, the collision process becomes less important and negligible. At very low temperatures, the main excitations in liquid ^4He are phonons. On the other hand, we note that 3PP are the most important process in the anomalous elementary excitation spectrum of liquid ^4He at very low temperatures and very small momenta.

Before Kirkpatrick and Dorfman, Ma¹⁷ and Popov¹⁸ obtained the same results, i.e., a damping factor on the order of $q^2 T^{-9}$, where q is the wave number of the disturbance in the calculation of the hydrodynamic eigenvalue describing second sound propagation. Comparing this with that of Kirkpatrick and Dorfman, we find the relation, $q^2 \eta / \rho_n \sim q^2 T^{-9}$, and thus have $\eta \sim T^{-5}$, where ρ_n is proportional to T^4 . Popov has also derived a T^{-5} dependence of η through the functional integral analysis, which turns out to be mainly the same contribution from 4PP in Landau-Khalatnikov theory.¹⁹

In the calculation for $\eta(T)$ and $\zeta(T)$ given by Kirkpatrick and Dorfman, $\eta(T)$ is proportional to T^{-5} , while the thermal conductivity $\kappa(T)$ is proportional to T^2 , and all four coefficients of the second viscosity have only a T^3 dependence for very low temperature. However, Eqs. (16)-(18) include not only T^3 terms but also an important T^{-1} dependence. As $T \rightarrow 0$, their four coefficients tend directly to zero. However, Eqs. (16)-(18) show a divergence, which is quite contrary to their results. We emphasize again the difference between contributions from 3PP and 4PP. The discrepancy in the results obtained by us and by Kirkpatrick and Dorfman is due to the fact that their hydrodynamic solution accommodates only 4PP, which does not appear at very low temperatures in the Landau-Khalatnikov theory, and breaks down

when 3PP are included, while our theory includes only 3PP, which are the main contribution to the transport coefficients near zero temperature and at very small momenta. We note that there are generally thirteen independent dissipation coefficients.²⁰ Here we only consider five coefficients and do not discuss the pressure and frequency variation²¹ of the coefficients of the second viscosity.

Figure 1 illustrates the temperature variations and magnitudes of the four coefficients of the second viscosity and the coefficient of the first viscosity. The above five coefficients are all positive. For very low temperatures (well below $T < 0.6$ K), the condition $\zeta_1^2 < \zeta_2\zeta_3$ holds. Comparing the order of magnitudes for the four coefficients, we can write $\zeta_3 > \zeta_1 > \zeta_2$, and all four coefficients have larger values than that of the coefficient of the first viscosity. We note that the thermal conductivity (κ) and five coefficients, as mentioned above, for thin liquid helium films have the same properties as those for bulk liquid helium.¹²

Figure 2 represents the values of the coefficients²² of the first and second viscosity as a function of temperature in the functional form by which they appear in the absorption coefficient of the second sound given by Khalatnikov. The behavior of this curve increases moderately as temperature decreases in the range $T > 0.2$ K and rapidly diverges near zero temperature. It shows a similar behavior to that in the high-temperature region ($T > 0.6$ K).

In conclusion, the coefficients of the second viscosity in bulk liquid helium exhibit a T^{-1} dependence for temperatures below 0.6 K, like that of the first viscosity, which is due to 3PP originating from the anomalous excitation spectrum of bulk liquid helium at low momenta and low temperatures. However, there are no experimental results. A precise measurement of the temperature variation of the second viscosities would be desirable.

This work was supported by a grant to Korea University from the BSRI, Ministry of Education, 1990, Republic of Korea, the Center for Thermal and Statistical Physics, and the US Office of Naval Research.

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Table 1. Parameters for bulk liquid helium

$n(\text{\AA}^{-3})$	$\Delta/k_B(\text{K})$	$q_0(\text{\AA}^{-1})$	μ	$c_0(\text{m/s})$	$\delta_1(\text{\AA}^2)$	$\delta_2(\text{\AA}^3)$	$\delta_3(\text{\AA}^4)$
2.18×10^{-2}	8.616	1.930	$0.153 m_{\text{He}}$	238.21	1.51 ± 0.13	3.25 ± 0.20	-16

Figure Captions

Figure 1. Temperature variation of the coefficient of the first viscosity (η) and the four coefficients of the second viscosity, ζ_1 ($-\zeta_4$), ζ_2 and ζ_3 . The curves represent only the magnitudes of these coefficients, where the units are g/cm \cdot s for η and ζ_2 , cm 2 /s for ζ_1 ($-\zeta_4$) and cm 5 /g \cdot s for ζ_3 .

Figure 2. Coefficients of the first and second viscosity as a function of temperature in the functional form by which they appear in the absorption coefficient of second sound given by Khalatnikov. The quantities ρ_s and ρ_n are the superfluid and normal densities, respectively.

Fig. 1

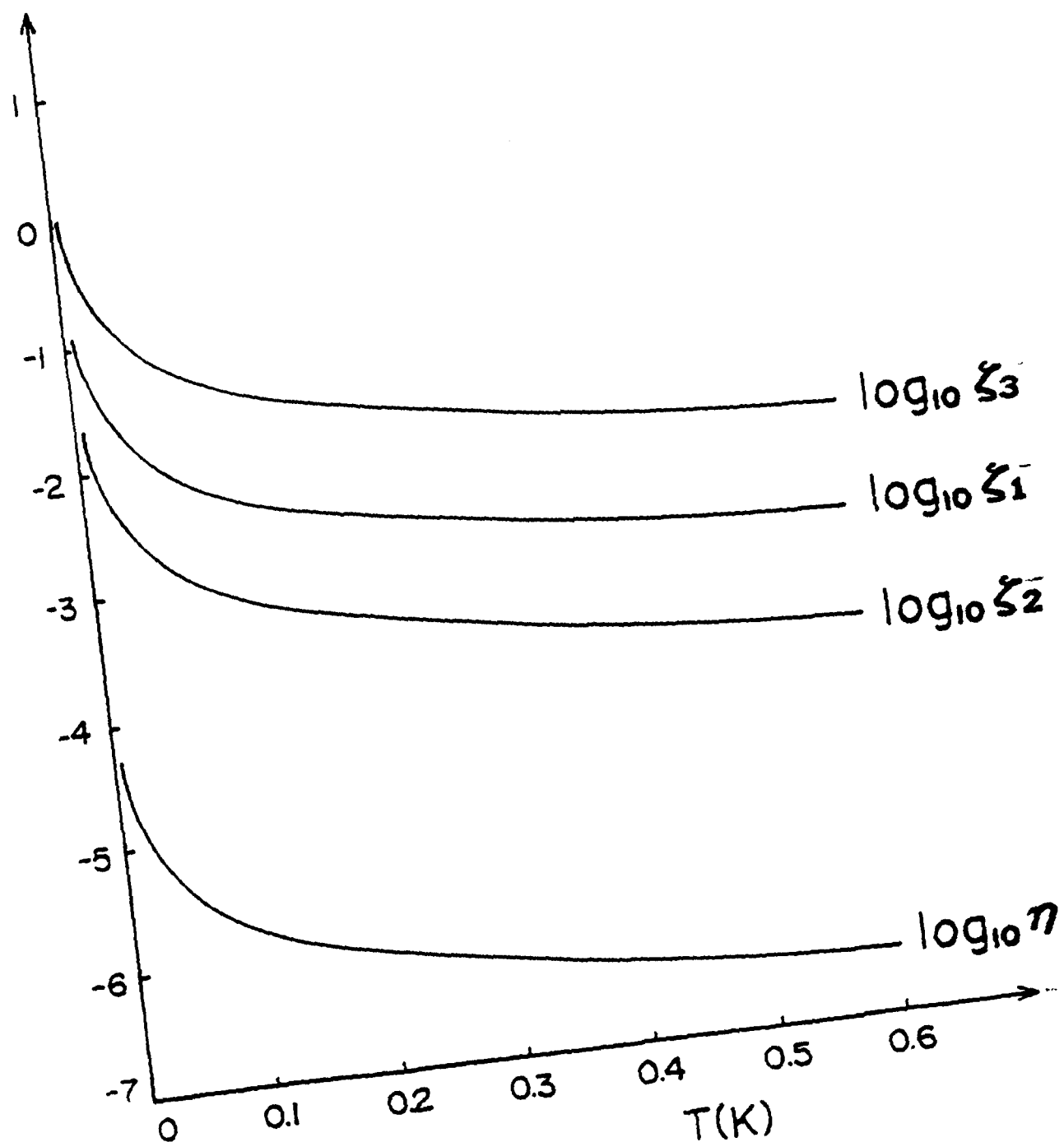


Fig. 2

